

# **Geochronology and Geology of late Oligocene through Miocene Volcanism and Mineralization in the Western San Juan Mountains, Colorado**

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## **Abstract**

Twenty-five new  $^{40}\text{Ar}/^{39}\text{Ar}$  ages from volcanic rocks and veins in the western San Juan Mountains clarify relationships between volcanism and mineralization in this classic area. Five calc-alkaline ash-flow sheets erupted from caldera sources (Ute Ridge, Blue Mesa, Dillon Mesa, Sapinero Mesa, and Crystal Lake Tuffs) from 28.6 to 27.6 Ma. This is a much more restricted time interval than previously thought and indicates that the underlying batholith rose and evolved very rapidly beneath the western San Juan Mountains. The new ages and geologic relations constrain the timing of joint resurgence of the Uncompahgre and San Juan calderas to between 28.2 and 27.6 Ma. The collapse of the Silverton caldera produced a set of strong ring fractures that intersected with graben faults on the earlier resurgent dome to produce the complex set of structures that localized the mid-Miocene epithermal gold veins.

Later calc-alkaline monzonitic to quartz monzontic plutons solidified at 26.5-26.0 Ma as the underlying batholith rose through its volcanic cover. A new age from lavas near Uncompahgre Peak supports earlier interpretations that these lavas were fed by nearby 26 Ma monzonite intrusions. Nearly all of these intrusions are associated with subeconomic Mo and Cu mineralization and associated alteration, and new ages of 26.40 and 25.29 Ma from the Ute-Ulay and Lilly veins in the Lake City region show that some of the most important silver and

base-metal veins were temporally and possibly genetically connected to these plutons. In addition, the Golden Fleece telluride vein cuts all of the post-Uncompahgre caldera volcanics in the area and is probably temporally related to this cycle, though its age of  $27.5 \pm 0.3$  Ma was determined by less precise U/Pb methods.

The 22.9 Ma Lake City caldera collapsed within the older Uncompahgre caldera structure but is petrologically unrelated to the older calc-alkaline activity. The distinctive suite of high-silica rhyolite tuff and alkaline resurgent intrusions indicates that it is closely related to the early stages of bimodal high-silica rhyolite-alkali basalt volcanism that accompanied the onset of extensional tectonism in the region. Both  $^{40}\text{Ar}/^{39}\text{Ar}$  ages and paleomagnetic data confirm that the entire caldera sequence formed in less than 330,000 years. Only weak quartz vein mineralization is present in the center of the caldera, and it appears to be related to leaching of metals from the intracaldera tuffs above the resurgent intrusion. Massive alunitization and weak Mo and Cu mineralization along the eastern ring fracture are associated with calc-alkaline lavas and stocks related to late stages of the caldera cycle. These calc-alkaline stocks also appear to be genetically and temporally linked to a radial pattern of barite-precious metal veins on the northeastern margin of the Lake City caldera.

## **Introduction**

The rich epithermal vein and breccia pipe deposits of the western San Juan Mountains have been used as a model of the relationship between epithermal mineralization and volcanic activity for the past century (Ransom, 1901; Cross and Larsen, 1935; Varnes, 1963). During the past two decades, great advances have been made in understanding the style of caldera-related volcanism and its relationship to ore deposits in this classic area (Steven and Lipman, 1976). Though almost all of the mineralization is spatially related to the calderas that formed from 29 to 27 Ma, Lipman and others (1976) demonstrated that the large epithermal vein deposits are 10-15 Ma younger. The caldera-forming eruptions produced fractures and faults suitable for later mineralization but appear to have depleted the associated magmatic systems of any ore fluids

capable of producing mineralization during the caldera cycle.

More recent studies by Slack (1980) identified base metal and precious metal veins that are mineralogically zoned and spatially distributed around the outside of the 23 Ma Lake City caldera. Although Slack (1980) proposed that these veins formed contemporaneously with the Lake City caldera, a U-Pb-isochron ( $27.5 \pm 0.3$  Ma) date on one of the richest of these veins indicates formation near the end of the earlier caldera cycle rather than during the Lake City caldera cycle (Hon and others, 1985). This in turn suggested the possibility of some mineralization in the western San Juan Mountains associated with the period of major caldera formation or the episode of calc-alkaline intrusive activity that immediately followed it. However, massive alunitization and porphyry-style mineralization of postcollapse lavas within the Lake City caldera are undoubtedly contemporaneous with Lake City caldera formation and with similar acid-sulfate alteration and mineralization at Summitville and Red Mountain Pass (Bove and others, 1990; Gray and Coolbaugh, 1994; Gilzean, 1984).

Our goal was to obtain more precise ages from a variety of fresh and mineralized rocks to clarify key relationships between caldera formation and mineralization in the western San Juan Mountains. We have obtained a series of new  $^{40}\text{Ar}/^{39}\text{Ar}$  ages from the main calc-alkaline ash-flow sheets and related younger calc-alkaline plutons, the ash-flows and lavas of the Lake City caldera cycle, and veins and other altered rocks in the Lake City region. Although these ages do not alter the general geological story of the western San Juan Mountains, they provide a much more precise chronological framework for interpreting durations of events and their relationship to mineralization. These ages are of similar quality to  $^{40}\text{Ar}/^{39}\text{Ar}$  ages from the eastern and central San Juan Mountains (Lipman and others, 1997; Lanphere, 1988), making chronological interpretations between the regions more comparable. The detailed ages from the Lake City caldera and surrounding veins call for a further re-evaluation of the timing of mineralization in this area and also allow testing of the paleomagnetic constraints on duration of the caldera cycle proposed by Reynolds and others (1986).

## Methods

The ages of 25 mineral separates (Appendix I) were determined using the  $^{40}\text{Ar}/^{39}\text{Ar}$  step-

heating technique. With the exception of two sericite samples that were hand separated, samples were crushed and sieved to recover the 125 to 250  $\mu$ m fraction. The concentrates were washed in 10 percent HCl in an ultrasonic bath to remove carbonate and were hand picked to remove grains that showed evidence of incipient alteration. Samples were irradiated for about 30 hours at 1 megawatt in the U.S. Geological Survey TRIGA reactor in Denver. Corrections for radiation-produced interfering isotopes of argon were made by applying measured production ratios for the interfering isotopes of argon produced in pure  $\text{CaF}_2$  and  $\text{K}_2\text{SO}_4$  irradiated along with the samples (Appendix I). Neutron flux during irradiation was monitored using hornblende standard MMhb-1, which has a K-Ar age of  $520.4 \pm 1.7$  Ma (Samson and Alexander, 1987). Errors of 0.1 percent in the calculated J-value were experimentally assessed by calculating the reproducibility of multiple monitors. Samples were heated in a low-background, resistively heated, double vacuum Ta-furnace in a series of eight to nineteen 20-minute-long steps. Isotopic abundances of argon were measured using a mass spectrometer operated in the static mode. All data were reduced using the decay constants and isotopic abundances suggested by Steiger and Jäger (1977). Age plateau criteria were based on Fleck and others (1977), whereby a plateau is defined by two or more contiguous gas fractions whose apparent ages are statistically indistinguishable at the 95 percent confidence level (Dalrymple and Lanphere, 1969) and which together total greater than 50 percent of the total  $^{39}\text{Ar}_k$  released. Plateau ages represent a weighted mean, where weighting is by the inverse of the analytical variance (Taylor, 1982). The error was determined using equations of Dalrymple and Lanphere (1981). For further details on this analytical method see Snee and others (1988). All ages listed in this publication are reported at the 1  $\sigma$  confidence level; previous K-Ar ages have been recalculated using the 1977 IUGS constants (Hon and Mehnert, 1983).

### *Early caldera cycles*

Collapse of the San Juan and Uncompahgre calderas took place about 28.4-28.2 million years ago in association with major ash-flow eruptions of the Sapinero Mesa Tuff and possibly

early eruption of the less-voluminous Dillon Mesa Tuff (Lipman and others, 1973; Steven and Lipman, 1976). The Uncompahgre caldera created an irregular-shaped depression about 20 km in diameter west and southwest of Lake City (Fig. 2a). The San Juan caldera formed nearly concurrently about 20 km west of the Uncompahgre caldera. Although related to ash-flow eruptions of the same composition and genesis, both calderas are discreet structures that form a composite, dumbbell-like shape, separated at present erosion levels by a slice of Precambrian granitic rocks. An intimate association of the two cupolas of magma, indicated by nearly concurrent caldera collapse, is evidenced by joint caldera resurgence to form an elliptical structural dome that extends across the apical portions of both calderas.

Initial collapse of the Uncompahgre caldera may have slightly preceded that of the San Juan caldera, triggered by eruption of the Dillon Mesa Tuff (Lipman and others, 1973). In general, the Dillon Mesa Tuff is a relatively thin, phenocryst-poor, rhyolitic ash-flow sheet, that is mineralogically similar to the overlying Sapinero Mesa Tuff. The Dillon Mesa Tuff stratigraphically overlies the Blue Mesa and Ute Ridge Tuffs, which were erupted respectively from the Lost Lake and Ute Creek calderas, also in the western San Juan Mountains (Fig. 1).

The Sapinero Mesa Tuff has been subdivided into three major units including the Sapinero Mesa, Eureka, and the Picayune Megabreccia members (Lipman and others, 1973). The outflow Sapinero Mesa member is a low-silica rhyolite (73% SiO<sub>2</sub>) that contains about 5 percent phenocrysts of sanidine and plagioclase in subequal proportions, plus biotite, and minor augite (Lipman and others, 1973). The Eureka member, the intracaldera equivalent of the Sapinero Mesa member, is a compound cooling unit of low-silica rhyolite tuff (70-72% SiO<sub>2</sub>) and generally contains 5-10 percent phenocrysts of sanidine, plagioclase, and sparse biotite and augite. This unit differs from outflow Sapinero Mesa Tuff in that it is intensely propylitized, contains abundant lithic fragments, and accumulated to great thickness. The Picayune Megabreccia member commonly lies stratigraphically below the Eureka member (Lipman, 1976b), and consists of a chaotic assemblage of pre-caldera rocks that slid from the oversteepened walls of the San Juan and Uncompahgre calderas. The megabreccia unit is intricately intermixed with variable amounts of ash-flow matrix indistinguishable from the interfingering and overlying Eureka Member.

The 27.6 Ma Silverton caldera, which is nested within the San Juan caldera (28.2 Ma) (Fig. 1), collapsed in response to eruption of the Crystal Lake Tuff (Lipman and others, 1976). The Crystal Lake Tuff, consists of low-silica rhyolite (71-72% SiO<sub>2</sub>) and forms a relatively small-volume ash-flow sheet in comparison with deposits related to other calderas in the San Juan volcanic field (Steven and Lipman, 1976); this unit contains relatively sparse phenocrysts of sanidine, plagioclase, and biotite.

The Crystal Lake Tuff is mostly absent within the Silverton caldera undoubtedly due to erosion within this relatively shallow subsided depression. Instead, a thick sequence of finely porphyritic dacitic-andesitic lavas comprise the dominant rock units within the Silverton caldera (Burbank and Luedke, 1969; Yager and others, 1998); these lavas are generally referred to as the Burns Member of the Silverton Volcanic Series (Lipman and others, 1973; Burbank and Luedke, 1969; Yager and others, 1998). This thick package of lavas largely erupted along the ring fracture zones of the earlier collapsed 28.2 Ma San Juan and Uncompahgre calderas, prior to collapse of the Silverton caldera (Lipman and others, 1976). Rocks overlying the Burns Member vary considerably throughout the Silverton caldera and generally consist of interbedded volcanoclastic sediments, mudflow breccias, and interbedded lavas. The rocks that overlie the Burns Member within and around the Silverton caldera are commonly referred to as the Henson Member of the Silverton Volcanics (Burbank and Luedke, 1969; Lipman and others, 1973). In their type localities, east of the Silverton caldera, the contact between the Burns and Henson Members is laterally consistent (Lipman and others, 1973); however, the contact geometry of these units within the Silverton caldera may not be nearly so regular.

The Eureka graben, which is a downdropped keystone fault zone along the crest of the elliptical resurgent dome of the coalesced San Juan-Uncompahgre calderas, is an important host to mineralization that post-dates these calderas by about 5-15 Ma (Lipman and others, 1976). In general, hydrothermal activity temporally related to these calderas caused regional propylitization with associated weakly disseminated pyrite (Slack and Lipman, 1979). Vertical zoning patterns are apparent within the propylitic assemblage, specifically in the area of the Eureka graben (Casadevall and Ohmoto, 1977; Burbank, 1960). Slack and Lipman (1979) attributed this vertical zonation to the presence of resurgent intrusions of the San Juan-

Uncompahgre calderas at depth beneath the Eureka graben.

Although altered and mineralized rocks are in close spatial association with the San Juan, Uncompahgre, and Silverton calderas, alteration and mineralization is rarely contemporaneous with caldera formation (Lipman and others, 1976; Slack and Lipman, 1979). The San Juan-Uncompahgre caldera cycle thus provided a favorable structural environment for later mineralization.

We refer the reader to a recent generalized geologic map of the Silverton caldera and surrounding areas (Yager et al, 1998) for reinterpretation of some of the previously mapped volcanic units. These reinterpretations are based on previous studies by Lipman and others, 1976, Lipman and others, 1973, Lipman and others, 1970, and new  $^{40}\text{Ar}/^{39}\text{Ar}$  data presented in this report.

*New  $^{40}\text{Ar}/^{39}\text{Ar}$  ages and interpretations:* Ten new  $^{40}\text{Ar}/^{39}\text{Ar}$  age determinations were made on outflow pyroclastic units from early calderas ( $> 23$  Ma) of the western San Juan volcanic field (Fig. 2a,b; Table 1). Sanidine sample UR-1 from outcrops of Ute Ridge Tuff southwest of Finger Mesa (Fig. 2a, loc. 1) has a slightly U-shaped spectrum (Fig. 3a) suggesting the presence of minor excess  $^{40}\text{Ar}$ , but a weighted mean based on steps 4-9, containing 57 percent of the  $^{39}\text{Ar}_k$  released, gives a weighted mean age 28.63 Ma that we consider to best represent the age of this sample. This is confirmed by an  $^{40}\text{Ar}/^{36}\text{Ar}$  vs.  $^{39}\text{Ar}/^{36}\text{Ar}$  isochron plot (steps 2-12) with a slightly elevated atmospheric intercept [ $(^{40}\text{Ar}/^{36}\text{Ar})_i$ ] of  $316 \pm 5$  which is greater than the atmospheric value of 295.5.

Sanidine (BM-2) from the Blue Mesa Tuff was obtained from a sequence of ash-flow tuffs on the north edge of Alpine Plateau (Fig. 2b, loc. 2). This sample has a relatively simple age spectrum (Fig. 3b) with a plateau age of  $28.40 \pm 0.07$  Ma. In contrast, the age spectrum for sanidine sample BM-3 from Blue Mesa Tuff east of Telluride (Potosi Peak; Fig. 2a, loc. 3) is somewhat discordant yielding a plateau age of  $28.30 \pm 0.05$  Ma; apparent ages within the spectrum show a gradual rise in the middle to higher temperature steps (Fig. 3c). An isochron plot using all the steps gives an age of  $28.59 \pm 0.2$  Ma with an atmospheric intercept [ $(^{40}\text{Ar}/^{36}\text{Ar})_i$ ] of  $231 \pm 15$ , indicating apparent argon loss. Although the isochron date is our best estimated age

for this sample, we use this age only to confirm the simple plateau age from sample BM-3 ( $28.40 \pm 0.07$  Ma), our preferred age for the Blue Mesa Tuff.

Sanidine from a single pumice (DM-3) collected from outcrops of Dillon Mesa Tuff on the south edge of Alpine Plateau (Fig. 2b, loc. 4) gives an age spectrum that is slightly discordant (Fig. 3d), but a weighted mean age using steps 3-9, gives a preferred age mean of  $28.38 \pm 0.05$  Ma. Sanidine from Dillon Mesa Tuff at Potosi Peak (DM-4, loc. 5) has a simple age spectrum with a plateau age of  $28.42 \pm 0.06$  Ma (Fig. 3e). Our preferred age from sample DM-3 ( $28.38 \pm 0.05$  Ma) and the plateau age from sample DM-4 ( $28.42 \pm 0.06$  Ma) are analytically indistinguishable at the 95 percent confidence level and yield an arithmetic mean age of  $28.40 \pm 0.04$  Ma.

Three sanidine samples were analyzed from outflow of the Sapinero Mesa Tuff. The  $^{40}\text{Ar}/^{39}\text{Ar}$  age spectra for all three samples are remarkably simple and easy to interpret. Sample SM-4 (Fig. 3f), collected from fiamme in vitrophyre near Gateway north of Lake City (Fig. 2b, loc. 6), gave a plateau age of  $28.22 \pm 0.07$ . Sample SM-5, which was collected from outcrops of the Sapinero Mesa Tuff southeast of Sapinero (Fig. 2b, loc. 7), yielded a plateau age of  $28.17 \pm 0.06$  Ma (Fig. 3g). Finally, sample SM-6 from an ash-flow sequence near Potosi Peak (Fig. 2a, loc. 8) gave a plateau date of  $28.18 \pm 0.05$  Ma (Fig. 3h). Data for all three samples overlap statistically at the 95 percent confidence level, yielding a weighted mean age of  $28.19 \pm 0.03$  Ma.

Sanidine sample CL-6 from a vitrophyre at the base of the Crystal Lake Tuff near Uncompahgre Peak (Fig. 2a, loc. 9) has a simple age spectrum with a plateau age of  $27.62 \pm 0.07$  Ma (Fig. 3i). The age spectrum for sanidine sample CL-7 (Fig. 3j) collected from Crystal Lake Tuff in South Clear Creek, near Hermit Lakes (Fig. 2a, loc. 10), is somewhat discordant, although the intermediated steps of the age spectrum give a weighted mean age of  $27.73 \pm 0.05$  Ma that probably represents a reasonable estimate of the age of this sample. However, given the complicated nature of this sample, we consider the date from the Nellie Creek sample CL-6 ( $27.62 \pm 0.07$  Ma) our preferred age of the Crystal Lake Tuff.

A summary of our new  $^{40}\text{Ar}/^{39}\text{Ar}$  dates for the pyroclastic units of the western San Juan volcanic complex is presented in Table 2. From these new data we can constrain early caldera-related volcanism in the western San Juan volcanic field to between 28.63 Ma (Ute Ridge Tuff)



and 27.62 Ma (Crystal Lake Tuff) within a variance of 0.88 to 1.13 million years at the 1 confidence level. In addition,  $^{40}\text{Ar}/^{39}\text{Ar}$  ages for the intervening Blue Mesa ( $28.40 \pm 0.07$  Ma), Dillon Mesa ( $28.40 \pm 0.04$ ) and Sapinero Mesa ( $28.19 \pm 0.03$  Ma) Tuffs record a very brief eruptive time interval ranging from 0.11 to 0.31 million years (1 ). The weighted mean or preferred ages of these units (Table 2), with the exception of the Blue Mesa and Dillon Mesa Tuffs, are analytically distinguishable at the 95 percent confidence level using the Critical Value Test of Dalrymple and Lanphere (1969).

#### *Regional 26-25 Ma calc-alkaline intrusions*

*Geology and previous age-related studies:* A large swarm of calc-alkaline intrusions was emplaced between 26 and 25 Ma over a broad region of the western San Juan Mountains. These intrusions range from large stocks at Mt. Wilson west of Ophir and Sultan Mountain near Silverton to smaller plugs intruded near Capitol City in the Lake City area (Fig. 2a). While the overall size of the exposed plutons decreases from west to east, this may be an artifact of erosion rather than a reflection of their actual size. These plutons vary from simple to complexly zoned and in many places are associated with veins and disseminated and stockwork Mo-Cu mineralization (Ringrose and others, 1986; Slack, 1976; Caskey, 1979; Pyle, 1980). Many of these intrusions are completely crystalline and cut through the entire ash-flow sequence, suggesting that they may represent cores of now-eroded stratovolcanoes that fed thick sequences of lavas nearby (Lipman and others, 1973). Alternatively, the widespread distribution of intrusions also suggests that they represent the uppermost portion of the underlying batholith rising into and consuming the earlier volcanic pile-- similar to the emplacement of the Boulder batholith into the Elkhorn Mountains Volcanics in Montana (Lipman, 1984).

Previous K-Ar determinations on biotite from the monzonitic Ophir and Sultan Mountain stocks (Fig. 2a) gave concordant dates with a weighted mean age of  $25.9 \pm 0.6$  Ma (Jackson and others, 1980). A weighted mean age of  $25.2 \pm 0.6$  Ma (Jackson and others, 1980) was also determined from two concordant K-Ar dates on biotite from slightly more evolved monzonite porphyry phases of the Sultan Mountain stock in the Middle Fork-Ophir Pass area near Silverton

(Fig. 2a) (Ringrose and others, 1986, Fig. 1, p. 358). A K-Ar date of  $25.7 \pm 0.6$  Ma was determined by H.H. Mehnert (*in* Slack, 1980) on biotite from one of several small monzonite to monzogranite porphyry stocks in the Capitol City area (Fig. 2a). Like the nearby Capitol City stocks, small monzonite to dacite porphyry intrusions in the Iron Beds and Matterhorn Peak areas (Fig. 2a) are also associated with zoned alteration and weak mineralization (Slack, 1976; Caskey, 1979; Pyle, 1980) and have K-Ar ages of  $26.6 \pm 0.4$  (hornblende) and  $25.2 \pm 2$  Ma (plagioclase), respectively (F. McDowell, written commun., 1994).

*New  $^{40}\text{Ar}/^{39}\text{Ar}$  ages and interpretations:* Three biotite separates from samples related to the 26-25 Ma period of intrusion and mineralization were analyzed for this study (Table 1). In addition, sanidine from the top of a thick sequence of lavas exposed near Uncompahgre Peak (Fig. 2a) (volcanics of Uncompahgre Peak; Lipman, 1976) was dated to test the hypothesis of Lipman and others (1973) that these lavas were extrusive equivalents of the monzonite intrusions.

Two samples (SM-1 and SM-2) from the Sultan Mountain stock, near Silverton (Fig. 2a, locs. 11, 12) overlap at the 95 percent confidence level and have a weighted mean age of  $26.60 \pm 0.04$  Ma. Both samples have slight humps in the middle spectrum region that probably reflect the presence of incipiently chloritized biotite grains. Sample SM-1 has a weighted mean age of  $26.56 \pm 0.04$  Ma (Fig. 3k), whereas SM-2 has a weighted mean age of  $26.66 \pm 0.06$  Ma (Fig. 3l). Although both biotites gave disturbed age spectra, we consider a weighted mean date of  $26.60 \pm 0.04$  Ma to be our best estimate of the cooling age of these samples.

Biotite MP-8 is from a monzonite intrusion near the Capitol City townsite, about 30 km northeast of Silverton (Fig. 2a, loc. 13). This sample yields a simple age spectrum (Fig. 3m) with a plateau age of  $26.39 \pm 0.1$  Ma, which represents the cooling age of this intrusion. Sanidine sample UPL-1 from dacitic lavas of the volcanics of Uncompahgre Peak (Fig. 2a, loc. 14) yielded a simple age spectrum (Fig. 3n) with a plateau age of  $25.63 \pm 0.04$  Ma.

The weighted mean age of  $26.60 \pm 0.04$  Ma from Sultan Mountain stock biotite samples (SM-1, SM-2) is statistically indistinguishable from the plateau age ( $26.39 \pm 0.1$  Ma) of sample MP-8 from an intrusion in the Capitol City area (Table 2). Although these ages compare well to

previous K-Ar determinations, late-phases of these intrusions such as documented in the Middle Fork-Ophir Pass area (25 Ma; Ringrose and others, 1986) are not represented in the present study. Still, these new ages show a minimum time break of about 1 million years between the end of early caldera-related magmatism in this area (27.6 Ma) and emplacement of these 26-25 Ma mineralized intrusions. The age of sanidine sample UPL-1 ( $25.63 \pm 0.04$  Ma) collected from the uppermost flows of the volcanics of Uncompahgre Peak represents the minimum age of this thick sequence of dacitic to andesitic lavas. As this sample represents a minimum age for this thick sequence of flows, we consider it to be close enough in proximity the 26.4 Ma date on the monzonite intrusion in Capitol City (Table 2) to corroborate the assumption of Lipman and others, (1973) that the Capitol City intrusions may have been the primary feeders for the volcanics of Uncompahgre Peak.

*Veins and porphyry-style alteration related to 26-25 Ma intrusions*

*Geology and previous age-related studies:* Previous studies of the Middle Fork-Ophir Pass, Capitol City, Iron Beds, and Matterhorn Peak areas (Fig. 2a) document a close spatial association between porphyry Mo-Cu mineralization, base-metal sulfide veins, and 26-25 Ma monzonite intrusions (Ringrose and others, 1986; Slack, 1980; Caskey, 1979; Pyle, 1980). A weakly mineralized Mo-Cu porphyry system present in the Middle Fork-Ophir Pass area is temporally and genetically related to a late quartz monzonitic phase (25 Ma) of the Sultan Mountain stock (Ringrose and others, 1986). At the Middle Fork-Ophir Pass locality, quartz-molybdenite stockwork veins associated with intense phyllic alteration are cut by molybdenite-bearing, base-metal veins present mostly on the margins of the porphyry system (McCusker, 1982). Widespread porphyry-style alteration in the Capitol City area (Fig. 2a) is also spatially associated with several small 26 Ma monzonite to monzogranite porphyry stocks. Veins in this area, which largely correspond to the early quartz-base metal assemblage of Slack (1980), commonly cut the margins of these intrusions and extend for short distances into surrounding volcanic country rock.

The same early quartz-base metal assemblage is also present in the Ute-Hidden Treasure vein of the Ute-Ulay mine (Fig. 2a), one of the most productive vein systems in the Lake City

area (Slack, 1980). Veins of the quartz-base metal assemblage are mostly present along Henson Creek west of Lake City (Slack, 1980), where most trend northeast, transverse to the ring fault of the Lake City caldera. However, unlike the early quartz-base metal veins of the Capitol City area, veins of the Ute-Ulay mine are not spatially associated with exposed and altered 26 Ma monzonitic intrusions. Lacking this relationship, earlier studies by Slack (1976, 1980) postulated a genetic relationship between the quartz-base metal veins and the 23 Ma Lake City caldera.

Previous K-Ar determinations from coarse-grained sericite related to porphyry-style phyllic alteration in the Middle Fork-Ophir Pass area gave ages of  $24.9 \pm 0.6$  Ma and  $25.0 \pm 0.6$  Ma (Ringrose and others, 1986); these ages overlap statistically with their quartz monzonite host intrusions that had a weighted mean K-Ar date of  $25.2 \pm 0.6$  Ma (Jackson and others, 1980). Base metal vein mineralization and alteration associated with monzonitic intrusions in the Capitol City, Iron Beds, and Matterhorn Peak areas were not previously dated. However, Lipman and others (1976) described haloes of intensely altered and pyritized rock surrounding the Capitol City intrusions that are truncated abruptly at the topographic wall of the Lake City caldera. Their findings clearly demonstrated that intrusion-related alteration at this locality preceded caldera collapse at 23 Ma.

*New  $^{40}\text{Ar}/^{39}\text{Ar}$  ages and interpretations:* Coarse-grained sericite (sample UHT-10) from the early quartz-base metal assemblage in the Ute-Hidden Treasure vein (Fig. 2a, loc. 15) was previously dated by H.H. Mehnert (*in* Slack, 1980) using the K-Ar method. However, the validity of this sample's apparent age ( $20.1 \pm 0.6$  Ma) has been questioned due to geologic inconsistencies and relatively large errors associated with the analytical technique (Slack, 1980; Hon and others, 1985). Because establishing accurate age constraints on this significant vein assemblage is important, we redated sericite from sample UHT-10 (Slack, 1980) by the  $^{40}\text{Ar}/^{39}\text{Ar}$  method. In addition, we obtained an  $^{40}\text{Ar}/^{39}\text{Ar}$  date on sericite from another quartz-base metal vein (Lilly mine; Irving and Bancroft, 1911) near Capitol City to further constrain vein and intrusive relationships observed there.

$^{40}\text{Ar}/^{39}\text{Ar}$  step-heating experiments suggest that 1M sericite (UHT-10) from the early quartz-base metal assemblage in the Ute-Hidden Treasure vein originally formed at about 26.4

Ma. The step-up in apparent age with increasing temperature as observed in the age spectrum (Fig. 3o) may indicate an original age of sericite formation as well as an apparent age of resetting. We consider the apparent age from step 5 ( $26.40 \pm 0.04$  Ma), one of the statistically best steps with highest radiogenic yields, to be the best estimate of the maximum age of the sericite. The apparent resetting at about 22.9 Ma probably records a younger thermal event, which will be discussed in a later section of this report. A sample of green, 1M/2M<sub>1</sub> sericite from the Lilly vein (LV-9) about 1 km north of Capitol City (Fig. 2a, loc. 16) rendered an  $^{40}\text{Ar}/^{39}\text{Ar}$  plateau age of  $25.29 \pm 0.05$  Ma (Table 1).

An original age of  $26.40 \pm 0.04$  Ma for the Ute-Hidden Treasure vein sericite (UHT-10) is analytically indistinguishable from that of Capitol City monzonite sample MP-8 ( $26.39 \pm 0.1$  Ma). However, sericite from the Lilly vein (LV-9;  $25.29 \pm 0.05$  Ma) is significantly younger than sericite from the Ute-Hidden Treasure vein, indicating that they formed during two distinct episodes of mineralization. However, these new ages clearly depict the close association between early quartz-base metal assemblage veins in the Lake City area and 26-25 Ma monzonite intrusions (Table 2).

### *Evolution of the Lake City caldera*

*Geology and previous age-related studies:* Collapse of the Lake City caldera postdated all other caldera-related eruptions in the western San Juan Mountains by more than 4 million years. The Lake City caldera is thought to be associated with bimodal magmatism related to the onset of extensional tectonism in this general region at about 25 Ma (Lipman and others, 1978). It is surrounded by the older Uncompahgre, San Juan, and Silverton calderas (Fig. 1), which formed from 28.4 to 27.5 Ma during an earlier period of volcano-tectonism (Steven and Lipman, 1976).

Initial pyroclastic eruptions from the Lake City caldera were accompanied by large-scale collapse along an arcuate ring fault zone, which also served to control later eruptive vents. The Sunshine Peak Tuff comprises three compositionally distinct ash-flow members (Fig. 4) that record eruption from a magma chamber that was zoned downward from high-silica rhyolite to quartz trachyte (Hon and Lipman, 1989; Hon, 1987b). The lower member of the Sunshine Peak Tuff, a high-silica rhyolite (76 percent  $\text{SiO}_2$ ) marks the onset of pyroclastic activity; it spread

widely from the source region and accumulated to a thickness of more than 900 m within the contemporaneously subsiding caldera (Hon and Lipman, 1989; Hon, 1987b). Subsequent pyroclastic eruptions resulted in recurrent caldera collapse; these eruptions first deposited a 300-m-thick rhyolite unit (74 percent  $\text{SiO}_2$ ), which forms the middle member of the Sunshine Peak Tuff. The middle member has two distinct pumice types: a high-silica rhyolite identical to that in the lower member, and a mafic trachyte (65 percent  $\text{SiO}_2$ ). The upper member is quartz trachyte (67-69 percent  $\text{SiO}_2$ ) and marked the final pyroclastic eruptions from the zoned magma chamber. No erosional breaks occur within this entire ash-flow sequence, indicating that all three members of the Sunshine Peak Tuff erupted in rapid succession (Hon and Lipman, 1989).

A large quartz syenite pluton was intruded into the intracaldera fill to causing resurgence of the Lake City caldera. Intrusion of quartz syenite was accommodated by asymmetric doming and uplift of more than 1 km along the north-central ring fault. The mineralogic, petrologic, and isotopic characteristics of the resurgent intrusions (Hon and Lipman, 1989; Hon, 1987b) indicate that they were derived from the same alkalic magma chamber that produced the caldera-forming ash-flow eruptions.

Continued volcanic activity produced a thick sequence of post-caldera-collapse lavas collectively referred to as the dacite of Grassy Mountain (63-66 percent  $\text{SiO}_2$ ) (Fig. 4). These calc-alkaline lavas and domal masses, which both predate and postdate caldera resurgence, accumulated within the large topographic scallop outside the ring fault on the eastern margin of the caldera.

The last phase of igneous activity within the Lake City caldera was marked by intrusion of the dacite of Red Mountain (63-66 percent  $\text{SiO}_2$ ) (Bove and Hon, 1992; Bove and others, 1990) and the quartz monzonite of Alpine Gulch (67-68 percent  $\text{SiO}_2$ ) along the east and northeastern sections of the ring fault, respectively (Fig. 4). These calc-alkaline intrusions are similar in major-element chemistry, mineralogy, and phenocryst textures, and have nearly identical isotopic compositions, suggesting derivation from a common magmatic source. Geophysical data (Grauch, 1987) indicate that a large intrusive body underlies the eastern portion of the caldera, and studies by Hon (1987b) suggest that this body represents the crystallized calc-alkaline

magma chamber that fed these intrusions. Geochemical and isotopic data) indicate that these intrusions as well as the dacite lavas of Grassy Mountain were derived from magma that evolved separately from the main alkaline magma chamber related to caldera eruptions and resurgent intrusion (Hon and Lipman, 1989).

Previous K-Ar determinations were made on 10 mineral separates from rocks ash-flow tuffs, resurgent intrusions, and pre-resurgence lavas representing all stages of development of the Lake City caldera (Lipman and others, 1970; Hon, 1987b; Lipman and others, 1976). The most reliable of these ages range between  $22.6 \pm 0.5$  Ma and  $23.7 \pm 0.4$  Ma; however, all of these ages within this apparent 1.1 million year time interval are statistically indistinguishable at the 95 percent confidence level. Based on these ages and associated errors, the absolute time span for caldera formation could vary from a maximum of 2 Ma (22.1 to 24.1 Ma) to a minimum of 0.2 Ma (23.1 to 23.3 Ma) at the 1 confidence level. Further restrictions on the duration of the Lake City caldera cycle have been inferred from paleomagnetic studies (Reynolds and others, 1986), which record emplacement of the ash-flow tuffs and the postcollapse lavas, and initial cooling of the resurgent intrusions during a reversed polarity chron. Based on seafloor records of reversed magnetic periods with the Earth's field from 24-22 Ma, Reynolds and others (1986) have estimated that the time span from eruption to resurgence of the caldera was probably less than 300,000 years.

*New  $^{40}\text{Ar}/^{39}\text{Ar}$  ages and interpretations:* Seven new  $^{40}\text{Ar}/^{39}\text{Ar}$  dates from mineral separates reported here (Table 1; Fig. 2a) span all stages of development of the Lake City caldera. This study was undertaken to ascertain whether individual phases of caldera activity could be distinguished using the higher analytical precision of the  $^{40}\text{Ar}/^{39}\text{Ar}$  step-heating method and to test the time-span estimate of Reynolds and others (1986).

The ages of sanidine samples from silicic (high-silica rhyolite; SP-11) and mafic (trachyte; SP-12) pumice from vitrophyre of the middle member of the Sunshine Peak Tuff (Fig. 2a, loc. 17, 18) precisely constrain the age of emplacement of this unit. The age spectra for both samples are simple (Figs. 3q and 3r), and give plateau ages of  $22.94 \pm 0.1$  and  $22.94 \pm 0.05$  Ma, respectively. Sanidine from sample DGM-13 from post-resurgence dacite of Grassy Mountain

lavas (Fig. 2a, loc. 19) gives a statistically identical plateau age of  $22.91 \pm 0.05$  Ma (Fig. 3s).

Sanidine from two dikes of the dacite of Red Mountain that crop out southeast (DRM-14) and northeast (DRM-15) of Red Mountain (Fig. 2a and 4, locs. 20, 21) were also analyzed. The age spectrum for sample DRM-14 (Fig. 3t) displays some excess argon and has a slightly elevated atmospheric intercept [ $^{40}\text{Ar}/^{36}\text{Ar}_i$ ] of  $302 \pm 3$  derived from an isochron plot of  $^{40}\text{Ar}/^{36}\text{Ar}$  versus  $^{39}\text{Ar}/^{36}\text{Ar}$ . This sample has an isochron date of  $22.96 \pm 0.04$  Ma after eliminating steps 13-14, which exhibit poor analytical reliability. The isochron date is our preferred age and is in close agreement with a statistically valid date of  $23.01 \pm 0.04$  Ma defined by eight temperature steps from 700°-1050°C that contain 41 percent of the released  $^{39}\text{Ar}_K$ . The age spectrum for sanidine sample DRM-15 (Fig. 3u) is relatively uncomplicated and has a plateau age of  $22.87 \pm 0.07$  Ma that is represented by four steps containing 86 percent of the released  $^{39}\text{Ar}_K$ .

Sanidine from a late-stage dike of the dacite of Red Mountain (DRM-16) (Fig. 2a, loc. 22 and Fig. 4) exhibits a relatively uncomplicated spectrum (Fig. 3v) with a plateau age of  $22.77 \pm 0.06$  Ma. The age spectrum from coexisting biotite (sample DRM-17 (Fig. 2a, loc. 23, and Fig. 3w) is complicated, clearly showing the effects of excess argon in the low and high temperature steps. A plateau age of  $23.24 \pm 0.04$  Ma from the intermediated temperature steps is strikingly discordant with our preferred age from the coexisting sanidine ( $22.77 \pm 0.06$  Ma). Such discordance is common in volcanic biotites, which sometimes have  $^{40}\text{Ar}/^{39}\text{Ar}$  ages that are older than those of coexisting sanidine by 0.1- 0.2 Ma (Harlan and others, 1998; Kellog and others, 1994). However, we consider this age unreliable as it is statistically older than all other Lake City  $^{40}\text{Ar}/^{39}\text{Ar}$  ages that are consistent with geologic data. We consider the 22.77 Ma age of the sanidine to be the best estimate for the age of the this late phase of the dacite of Red Mountain intrusions.

Excluding biotite sample DRM-17, all of the above-discussed ages related to Lake City caldera volcanic events are statistically indistinguishable at the 95% confidence level and yield a weighted mean age of  $22.93 \pm 0.02$  Ma. The maximum age difference within this set of samples at the 1  $\sigma$  level is 330,000 years. Our maximum determined age variance for the lifespan of the caldera is in close agreement with the 300,000-year time span estimated by Reynolds and others (1986), emphasizing the benefit of using these techniques collaboratively.



### *Hydrothermal activity and mineralization related to the Lake City caldera*

*Geology and previous age-related studies:* Hydrothermal systems were established both within the core of the Lake City caldera over the cooling resurgent plutons, and along and adjacent to the eastern margin of the caldera contemporaneous with emplacement of late calc-alkaline intrusions. Convective circulation of large volumes of meteoric water around the resurgent plutons and along the western and northern margins of the caldera was related to the formation of veins and associated alteration along extensional faults in the resurgent dome (Hon, 1987a). Veins that formed above the resurgent intrusions appear to have scavenged metals largely from the intracaldera Sunshine Peak Tuff, and have lower base-metal contents than similar veins peripheral to the intrusions (Hon, 1987b). This interpretation is confirmed by lead isotope studies (Sanford, 1992) showing that veins above the intrusions have Pb-isotopic ratios compatible with a lead source from the Sunshine Peak Tuff. Veins on the western margin of the caldera, however, have Pb-isotopic ratios indicating that hydrothermal fluids interacted with less radiogenic, pre-caldera andesites (Lipman and others, 1978), whereas veins on the east side of the caldera have significantly more radiogenic Pb-isotopic ratios (Sanford, 1992), suggesting that vein-related hydrothermal fluids that circulated deeply along the margins of the resurgent pluton interacted with underlying radiogenic Precambrian crystalline rocks.

Massive alunitization (roughly 70 million metric tons of alunite) of postcollapse lavas and intrusions on Red Mountain formed by degassing of sulfur-rich dacitic magmas emplaced along the eastern ring fracture zone (Fig. 4)(Bove and others, 1990). Alteration is zoned vertically from alunite downward into phyllic and finally into a deeper potassic assemblage related to emplacement of one or more dacite porphyry intrusions. Subeconomic Mo and Cu mineralization also increases with depth and proximity to the deeper potassic alteration assemblage (Bove and Hon, 1989). Replacement alunite, related to the ascent of buoyant magmatic vapor plumes, makes up the largest proportion of alunite at Red Mountain (Bove and others, 1990); however, late-stage, coarse-grained vein alunite is present locally and has been interpreted to have formed by decompression of magmatic steam in open fractures (Bove and others, 1990; Rye and others, 1992). A weakly mineralized quartz monzonite intrusion in nearby Alpine Gulch (Fig. 4) is genetically associated with the dacite of Red Mountain intrusions (Hon,

1987b). The Alpine Gulch intrusion has features associated with Cu and (or) Mo mineralization including fragmental dikes, tourmaline breccias, magnetite veinlets, and quartz veins containing pyrite, hematite, sphalerite, galena, and chalcopyrite (Hon, 1987a). However, alteration haloes are conspicuously absent around this intrusion.

Slack (1980) noted that veins on the east and north sides of the Lake City caldera fill fractures roughly perpendicular to the ring fault that appear to form a radial pattern around the Red Mountain area. This pattern of radial veins that contain the late barite-precious metal assemblage described by Slack (1980) was postulated to be related to emplacement of the 23 Ma dacite of Red Mountain intrusions (Slack, 1980). Thin veinlets of this late barite-precious metal assemblage are present in the Ute-Hidden Treasure vein of the Ute-Ulay mine (Fig. 2a) and are shown by Slack (1980, Fig. 4) to cut late ore shoots of the quartz-base metal assemblage. Mixing of meteoric water off the resurgent dome of the caldera, peripheral to the sulfate-rich magmatic plume, may have caused flushing of sulfate from the hydrothermal system into the surrounding radial vein systems (Hon, 1987b).

Previous K-Ar determinations were made on replacement and vein alunite from the Red Mountain complex on the east side of the 23 Ma Lake City caldera by Mehnert and others (1979). Replacement alunite yielded an age of  $22.9 \pm 0.8$  Ma, whereas an age of  $23.3 \pm 0.6$  Ma was determined on paragenetically later vein alunite. Studies by Hon and others (1985) disproved earlier assertions by Slack (1980), who claimed that the historically productive Golden Fleece vein (Irving and Bancroft, 1911) geographically situated among barite-precious metal veins on the east side of the Lake City caldera (Slack, 1976, 1980) was contemporaneous with the 23 Ma Red Mountain hydrothermal system. Although originally thought to be part of the barite-precious metal assemblage (Slack, 1980), late-stage ore minerals from the Golden Fleece vein are mineralogically distinct containing abundant gold and silver tellurides intergrown locally with minor colloform pitchblende (Hon and others, 1985); pitchblende is unknown elsewhere in the Lake City area (Slack, 1976; Hon and others, 1985). A U-Pb isochron age of  $27.5 \pm 0.3$  Ma and well documented geologic relations (Hon and others, 1985) clearly indicate that formation of the Golden Fleece vein preceded collapse of the Lake City caldera.

*New  $^{40}\text{Ar}/^{39}\text{Ar}$  ages and interpretations:* Coarse-grained vein alunite from Red Mountain (sample CA-18) (Figs. 2a, loc. 24, and Fig. 4) exhibits a relatively simple spectrum (Fig. 3x). Two steps yield a plateau age of  $23.11 \pm 0.04$  Ma, but this age is statistically older than  $^{40}\text{Ar}/^{39}\text{Ar}$  dates for unaltered host rocks. The reason for this discrepancy is unknown, but may be due to the unrecognized presence of uniformly distributed excess  $^{40}\text{Ar}$ . Because the alunite plateau date is greater than the host rocks we consider this age unreliable. Overall, we consider the weighted mean  $^{40}\text{Ar}/^{39}\text{Ar}$  age from all Lake City caldera samples (22.93 Ma) as the preferred age of contemporaneous alunite formation. Similar incongruously old  $^{40}\text{Ar}/^{39}\text{Ar}$  dates have also been recorded for replacement alunite from the 23 Ma Summitville deposit in the eastern San Juan Mountains (S. Harlan, oral commun., 1995). As at Red Mountain, these dates postdate the 23.0 Ma dacite porphyry host rock by 100,000 to several hundred thousand years. Alunite from the Summitville mine shows evidence of excess argon in the age spectra, which combined with the old apparent ages from both areas, may indicate an inherent problem in the isotopic dating of some alunites.

$^{40}\text{Ar}/^{39}\text{Ar}$  studies of 1M sericite (UHT-10) from the Ute-Hidden Treasure vein located just outside the northern ring fault of the Lake City caldera (Fig. 2a), may indicate both an original age of sericite formation and an apparent age of resetting (Fig. 3o). As discussed previously (see section on 26-25 Ma veins), an apparent age of  $26.40 \pm 0.04$  Ma is our best estimate of the maximum age of the sericite. However, this sample appears to have experienced partial  $^{40}\text{Ar}$  loss at about 22.9 Ma (steps 1 and 2) and may record the effects of a younger thermal event. This event may be related to hydrothermal fluids associated with the formation of late-stage, barite-precious metal veins < 40 m away. Scanning electron microscope studies of this sample reveal two discreet populations of sericite. We interpret the shape of the spectrum to reflect the combined effects of argon released from both mica populations. The earlier-formed, coarser sericite degassed primarily at higher temperatures, whereas the younger and finer mica fraction degassed at lower temperatures.

Although fission track data for zircon from the Capitol City area (Johnston and Naeser, 1976) probably record a younger thermal event related to the 22.9 Ma Lake City caldera cycle, thermal effects of this event were apparently insufficient to completely reset the  $^{40}\text{Ar}/^{39}\text{Ar}$  system

of sericite in the nearby Lilly vein (sample LV-9; Table 1; Fig. 2a). Thus by analogy thermal effects from the Lake City caldera likely were also insufficient and therefore did not reset the  $^{40}\text{Ar}/^{39}\text{Ar}$  systematics of sericite within the Ute-Hidden Treasure vein. In addition, the absence of Lake City caldera-age intrusions north of the ring fracture precludes resetting due to local intrusive activity. Thus by inference we suggest that the late barite-precious metal assemblage in the Ute-Hidden Treasure vein system formed at 22.9 Ma, and that this age most probably relates the radial barite-precious metal veins on the east side of the caldera to intrusive and hydrothermal activity at Red Mountain, as proposed earlier by Slack (1980).

### *23 Ma activity in the Silverton area*

*Red Mountains district:* Some of the richest ore in the Silverton area was mined from small silicified breccia pipes in the Red Mountains district (Fig. 2a). Orebodies within the oxidized portions of the breccia pipes were irregular in shape and typically consisted of carbonates of lead and iron, as well as lead sulfates, iron oxides, sphalerite, and miscellaneous arsenates (Fisher and Leedy, 1973). Below the oxidized zone, sulfide ores of pyrite, enargite and lesser chalcopyrite, galena, tetrahedrite, and sphalerite were present as irregular masses in altered volcanic rocks. Similar-aged ore deposits are also found in the vicinity of Prospect Gulch, just east of Red Mountain No. 3 (Nash, 1975, Bove and others 1998). However in comparison to the Red Mountain Pass deposits, ore minerals in the Prospect Gulch area are more confined to preexisting faults and spatially associated hydrothermal breccias zones. Although hydrothermal breccias are common in the Prospect Gulch area (Bove and others 1998; Nash, 1975; Fisher and Leedy, 1973.), surficial exposures of the classic mineralized breccia bodies --as observed in the Red Mountain Pass area--are largely absent (Bove et al, 1998). Sanidine and biotite from dacite porphyry intrusions spatially associated with these mineralized breccias yield slightly discordant K-Ar dates of  $21.9 \pm 0.3$  and  $24.0 \pm 0.4$  Ma, respectively (Hon and Mehnert, 1983).

These dated intrusions near Red Mountain Pass are nearly identical in composition to small plugs of dacite porphyry in the vicinity of Red Mountain No. 3 and Corkscrew Gulch, located immediately to the east (Fig. 2a). Intrusion of dacite porphyry in the vicinity of Red Mountain No. 3 is associated with high-level, acid-sulfate alteration and silicified hydrothermal

breccias that contain low-grade gold and silver values (Matlock and Hollister, 1990). Gold at this site averages about 0.03 oz/ton and is present as the native metal and in electrum, along with pyrite, enargite, and covellite (J. Matlock, oral commun., 1995).

Excellent rock exposure in the Red Mountain Pass and Prospect Gulch areas has allowed detailed zonation studies of hydrothermal of alteration assemblages within this complex acid-sulfate hydrothermal system. Pervasive quartz-sericite-pyrite-altered rock (QSP) is commonly exposed at the ground surface (Bove and others, 1998) and in places reflects a zonation upward and away from a deeper, potassic alteration assemblage typical of mineralized Mo-porphyry systems (Gilzean, 1984). Surface mapping and careful paragenetic studies demonstrate that structurally controlled zones of quart-alunite alteration transition outward into pyrophyllite, dickite, and (or) propylitic assemblages; whereas the collective acid-sulfate zones are commonly superimposed over broad intervening expanses of QSP-altered rock (Bove and others, 1998; Bove, unpub. data). Both acid-sulfate and pervasive QSP alteration in the Red Mountain Pass and Prospect Gulch areas is intimately associated and appears to be coeval with intrusion of dacite porphyry.

Dacite porphyry in the vicinity of Red Mountain No. 3 that has been replaced by alunite of hypogene origin (Bove and Rye, unpub. data), which has a K-Ar age of  $23.1 \pm 0.6$  Ma (2 ) (Gilzean, 1984). Statistically identical K-Ar dates of  $22.4 \pm 0.3$  Ma (sanidine) and  $23.6 \pm 0.4$  Ma (biotite) from a similar intrusion in the Corkscrew Gulch area (Gilzean, 1984) further confirms the association between 23-Ma mineralized breccias and dacite porphyry intrusion in the Red Mountains district.

Interestingly, these intrusions are texturally and compositionally similar to alunitized and mineralized dacite porphyry intrusions at Red Mountain, near Lake City (22.8 Ma; this study) and at the Summitville mine in the eastern San Juan Mountains ( $^{40}\text{Ar}/^{39}\text{Ar}$  age of 23.0 Ma; S. Harlan oral commun., 1995).

#### *19-17 Ma rhyolite intrusions north and south of the Lake City caldera and associated mineralization*

A series of silicic alkalic rhyolite intrusions and one extrusive dome was emplaced along

the northern margin of the Uncompahgre caldera about 18.8 Ma (Fig. 2a). These rhyolites are highly enriched in U, Li, Th, Be, Mo, and F and are similar petrogenetically to the F-rich, topaz rhyolites described by Burt and Sheridan (1980). The rhyolite bodies are characterized by erratic concentrations of uranium along their fractured margins (Slack, 1976; Steven and others, 1977) and contain late fluorite and topaz as vapor-phase vug-fillings. The volatiles H<sub>2</sub>O and HF were probably depleted during the cooling and crystallization of these magmas and lost as volcanic emanations from fumaroles (Zielinski and others, 1977); outside of local fumarolic alteration and devitrification, these intrusions and the surrounding host rocks are mostly unaltered.

Dikes of high-silica rhyolite associated with mineralized pebble dikes, uranium-mineralized fractures, fluorite, and anomalous molybdenum and tungsten are also present about 2-3 km south of the Lake City caldera, just southwest of the Sherman townsite (Fig. 2a). In contrast to the 18.8 Ma high-silica rhyolites to the north, these dikes are strongly hydrothermally altered, as is the surrounding granite, and are cut by thin veinlets of microplitic quartz, pyrite, and sericite. As these rocks have many of the characteristic signatures of Climax-type Mo-porphyry deposits (White and others, 1981; ), they were the focus of considerable exploration activity in the late 1970's through early 1980's.

South of the Lake City caldera and north of the former townsite of Sherman, a major mineralized structure is hosted almost entirely within a 30-m-thick diabase dike that cuts Precambrian granite (Sanford and others, 1991). The mineralized vein structure, known as the Black Wonder vein (Fig. 2a), is along a highly sheared zone that contains breccia fragments of the diabase dike and the granite. Cockscomb quartz is the dominant vein material and is accompanied by later fluorite and calcite, plus minor adularia, pyrite, chalcopryrite, galena, and barite. Chalcopryrite and pyrite are also disseminated throughout the brecciated wall rock.

Earlier K-Ar determinations from an alkali rhyolite intrusion on the northern margin of the Uncompahgre caldera yielded an age of  $19.1 \pm 0.2$  Ma (Lipman and others, 1976). This age is confirmed by six nearly identical K-Ar ages (Mehnert and Hon, unpublished data) from as many of these rhyolites that have a weighted mean age of  $18.8 \pm 0.4$  Ma (Table A3). Previously unpublished K-Ar determinations on sanidine from one of the high-silica rhyolite dikes in the Cuba Gulch area yielded a statistically younger age of  $17.11 \pm 0.3$  Ma (Table A3).

The age spectrum (Fig. 3y) for adularia separated from the Black Wonder vein (sample BWV-19) is slightly U-shaped, suggesting the presence of excess  $^{40}\text{Ar}$ . This sample yielded a plateau age of  $16.52 \pm 0.03\text{Ma}$  over steps 6-14 with 50 percent of the released  $^{39}\text{Ar}_k$ . An  $^{40}\text{Ar}/^{36}\text{Ar}$  vs.  $^{39}\text{Ar}/^{36}\text{Ar}$  isochron plot of using all the steps gives an age of  $16.47 \pm 0.02\text{ Ma}$  (Table 1) with a slightly elevated atmospheric intercept [ $(^{40}\text{Ar}/^{36}\text{Ar})_i$ ] of  $305 \pm 2$ , which is only slightly higher than the atmospheric value of 295.5. We consider the isochron date ( $16.47 \pm 0.02\text{ Ma}$ ) the preferred age for this sample due to the presence of minor excess  $^{40}\text{Ar}$ .

The 16.5 Ma date for the Black Wonder vein is the first age to document post-23 Ma vein mineralization in the Lake City area. The similarity in age between the Black Wonder vein and the mineralized rhyolite in Cuba Gulch (17.1 Ma) suggests the likelihood of a genetic association between mineralized veins and intrusion of high-silica rhyolite in this area. The rhyolites to the north of the caldera may be high-level and volatile-poor precursors to the deeper unexposed rhyolite intrusions beneath the Cuba Gulch area.

### **Discussion and Summary**

Our new  $^{40}\text{Ar}/^{39}\text{Ar}$  isotopic dates allow establishment of a significantly more refined chronology of caldera formation and mineralization in the western San Juan Mountains. From these data we document the geochronology of the following events: (1) formation of the Ute Creek (Ute Ridge Tuff), Lost Lake (Blue Mesa Tuff), San Juan-Uncompahgre (Dillon Mesa and Sapinero Mesa Tuffs), and Silverton calderas between 28.6 and 27.6 Ma; (2) emplacement of 26.5-25 Ma intermediate-composition intrusions and related subeconomic Mo-Cu porphyry and associated vein mineralization; (3) eruption and resurgent doming of the 22.9 Ma Lake City caldera and temporally associated mineralization in the Lake City area; and (4) emplacement of 18-17 Ma high-silica rhyolite intrusions on the margins of the Lake City caldera and related 16.5 Ma vein mineralization.

Previous K-Ar dates for the Ute Ridge Tuff (30.1 and 28.1 Ma) and Fish Canyon Tuff (27.8 Ma) loosely documented the ages of pre-Lake City-age calderas of the western San Juan Mountains (Lipman and others, 1976). New  $^{40}\text{Ar}/^{39}\text{Ar}$  dates, however, precisely constrain the

time interval (0.8 to 1.1 million years at the 1  $\sigma$  level) between emplacement of the Ute Ridge (28.63 Ma) and Crystal Lake Tuffs (27.62 Ma) and show the brief intervening eruptive chronology of the Blue Mesa (28.40 Ma), Dillon Mesa (28.40 Ma), and Sapinero Mesa (28.19 Ma) Tuffs. Integrating our new dates with previously established geologic relationships, we can now determine the time interval for joint resurgence of the San Juan-Uncompahgre calderas. Studies by Luedke and Burbank (1968) showed that resurgent doming began shortly after collapse of the Sapinero Mesa Tuff, before early accumulation of caldera-filling lavas. However, evidence of late stages of resurgence has been recognized in key exposures of the Crystal Lake Tuff (Lipman and others, 1973; P.W. Lipman, written commun., 1998), indicating that resurgent doming took place from about 28.2 to 27.6 Ma. Our new  $^{40}\text{Ar}/^{39}\text{Ar}$  ages are of similar quality to those of Lipman and others (1997) and Lanphere (1988), now enabling correlation of regional ash-flow stratigraphy across the entire San Juan volcanic field.

A regional magmatic event beginning about 26.5 Ma resulted in intrusion of monzonite and quartz monzonite from Wilson Mountain northeast to Capitol City (Fig. 2a). This event was probably related to intrusion of a high-level batholith into its own volcanic cover. Ages of sericite from quartz-base metal veins near Capitol City (25.3 Ma) and Lake City (26.4 Ma) confirm relationships observed in the Middle Fork-Ophir Pass area indicating that these veins formed coevally with various phases of the monzonite intrusions. These new ages indicate a minimum hiatus of about 1 million years between mineralization related to the 26-25 Ma intrusions and pyroclastic eruptions from the 27.6 Ma Silverton caldera.

The Lake City caldera is the youngest of more than 15 collapse calderas that have been recognized within the San Juan volcanic field (Steven and Lipman, 1976; Lipman and others, 1997). Six new  $^{40}\text{Ar}/^{39}\text{Ar}$  dates are indistinguishable at the 95 percent confidence level and have a minimum and maximum apparent age variance of 80,000 to 330,000 years at the 1  $\sigma$  confidence level. A weighted mean of these determinations yields an age of  $22.93 \pm 0.02$  Ma. A maximum time restriction of 330,000 years for the evolution of the Lake City caldera is consistent with paleomagnetic studies of Reynolds and others (1986); however, our minimum age variance of 80,000 years is more similar to durations known from some other well-dated Pleistocene calderas



(Gansecki and others, 1998; Gazis and others, 1995; Hildreth and others, 1984).

Intrusion of the calc-alkaline dacite of Red Mountain late in the Lake City caldera cycle is clearly linked to massive alunitization and related subeconomic Mo-Cu porphyry mineralization at depth. Radial veins of the late barite-precious metal assemblage (Slack, 1980) located 2-3 km north and east of Red Mountain (Fig. 4) are also probably genetically related to the dacite of Red Mountain intrusions. We interpret the sericite from the Ute-Hidden Treasure vein, which originally crystallized at  $26.40 \pm 0.04$  Ma, to have been partially reset at  $22.9 \pm 0.1$  Ma, perhaps by hydrothermal fluids related to nearby veins of the late-stage barite-precious metal assemblage. Based on these data, we concur with the conclusion of Slack (1980) that the late barite-precious metal veins distributed radially around the east side of the Lake City caldera were associated with 23 Ma hydrothermal activity at Red Mountain. Recharge of meteoric water from the top of the resurgent dome of the caldera may have resulted in the flushing of sulfate and metals from the Red Mountain hydrothermal system into the surrounding moat zone where these veins formed.

Intrusion of compositionally and petrographically similar dacite porphyry took place regionally throughout the San Juan volcanic field at about 23 Ma. Calc-alkaline dacite porphyry intrusions at Red Mountain Pass north of Silverton, Summitville (Gray and Coolbaugh, 1994), and those at Red Mountain near Lake City aside from being related to significant mineralization were all rich in sulfur and genetically associated with large, acid-sulfate alteration systems (Gilzean, 1984 ; Lipman and others, 1976; Gray and Coolbaugh, 1994; Bove and others, 1990). Mass-balance studies of hydrothermally altered rocks at Red Mountain (Lake City) document that nearly 14 million metric tons of sulfur were derived from the underlying dacitic magmas (Bove, 1988). Although only speculative, one possible mechanism for sulfur enrichment in these 23 Ma dacitic magmas could have been upward migration of a fluid phase derived from an underplating basaltic magma similar to processes related to the 1991 high-SO<sub>2</sub> eruptions at Mount Pinatubo (Pallister and others, 1992). As extrapolated to the 23 Ma setting in the San Juan volcanic field, regional extension and crustal thinning may have promoted the ascent of basaltic magma to higher crustal levels, which then gave rise to the sulfur-rich dacitic

magmas.

Economically important post-23 Ma vein mineralization in the western San Juan Mountains appears to be closely associated with intrusion of high-silica alkali rhyolite (Lipman and others, 1973). The distinctive early Miocene (23-16 Ma) quartz-bearing rhyolites in the San Juan Mountains are part of a bimodal igneous suite associated with extensional tectonism that began about 25 Ma. These rhyolite intrusions, such as the dikes in Cuba Gulch, south of Lake City (Fig. 2a), and those around Red Mountain Pass north of Silverton (Fig. 2a), are petrologically very similar to Climax-type high-silica rhyolites (White and others, 1981; Lipman and others, 1976) that are associated with large molybdenum porphyry systems in the Western United States.

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